CHAPTER 4

TROPOSPHERIC PERFORMANCE CONSIDERATIONS

4.1 PATH PROPAGATION

Trans-horizon propagation can occur by refraction, by forward tropospheric scatter or by both. For transmission paths extending only slightly beyond line-of-signt diffraction will be the dominant mode and scatter may be neglected. Conversely for very long paths, the diffraction mode can be neglected. In intermediate cases, both modes must be considered and the results combined to obtain the reference transmission loss.

4.1.1 Basic Theory

The diffraction mode of propagation is discussed in chapter 2. Experiments conducted at distances well beyond the normal horizon, primarily during the years from 1935 to 1950 show that a remarkable persistant weak field in the VHF, UHF and SHF bands existed and were much stronger than could be explained on the basis of simple diffraction theory. In the early 1950's these persistant long distance fields came to be called "scatter" fields. The rapid and intense short-term fading characteristic naturally brings to mind the concept of multiple source scattering propagation. Many theorys have been presented to explain the mechanics of this type of communications. Some of those theories have been withdrawn or modified because of new data presented by the numerous agencies working on this phenomenon. The theory presented here is probably the most widely used.

Although the atmosphere becomes uniformly less dense with increasing height above the earth, certain irregularities exist in this gradient as evidenced by the twinkling of stars and sudden bouncing of aircraft. These perturbations occur in blobs which are large compared to the wavelength used in scatter communications and present an index of refraction which differs from that of the surrounding medium. This abrupt change in the index of refraction causes a refraction or "scattering" of an electromagnetic wave. This refraction is only partial at best, since most of the energy propagated continues in a forward direction; however, enough energy is scattered toward the earth for large area, narrow beam antennas to capture it. Direct airborne measurements of the refractive index variations indicate that they are characterized by a spectrum of scales extending over a range from a few centimeters to several kilometers, and the intensity decreases on the average exponentially with increasing height. Figure 4-1 illustrates the scatter model. Both the transmit and receive antennas are aimed to the same spot in the sky. Since the bending or scattering effects are small, more energy is deflected toward the receiving antenna if the scatter angle is small, that is if both the transmit take off and receiving antenna angles are small.

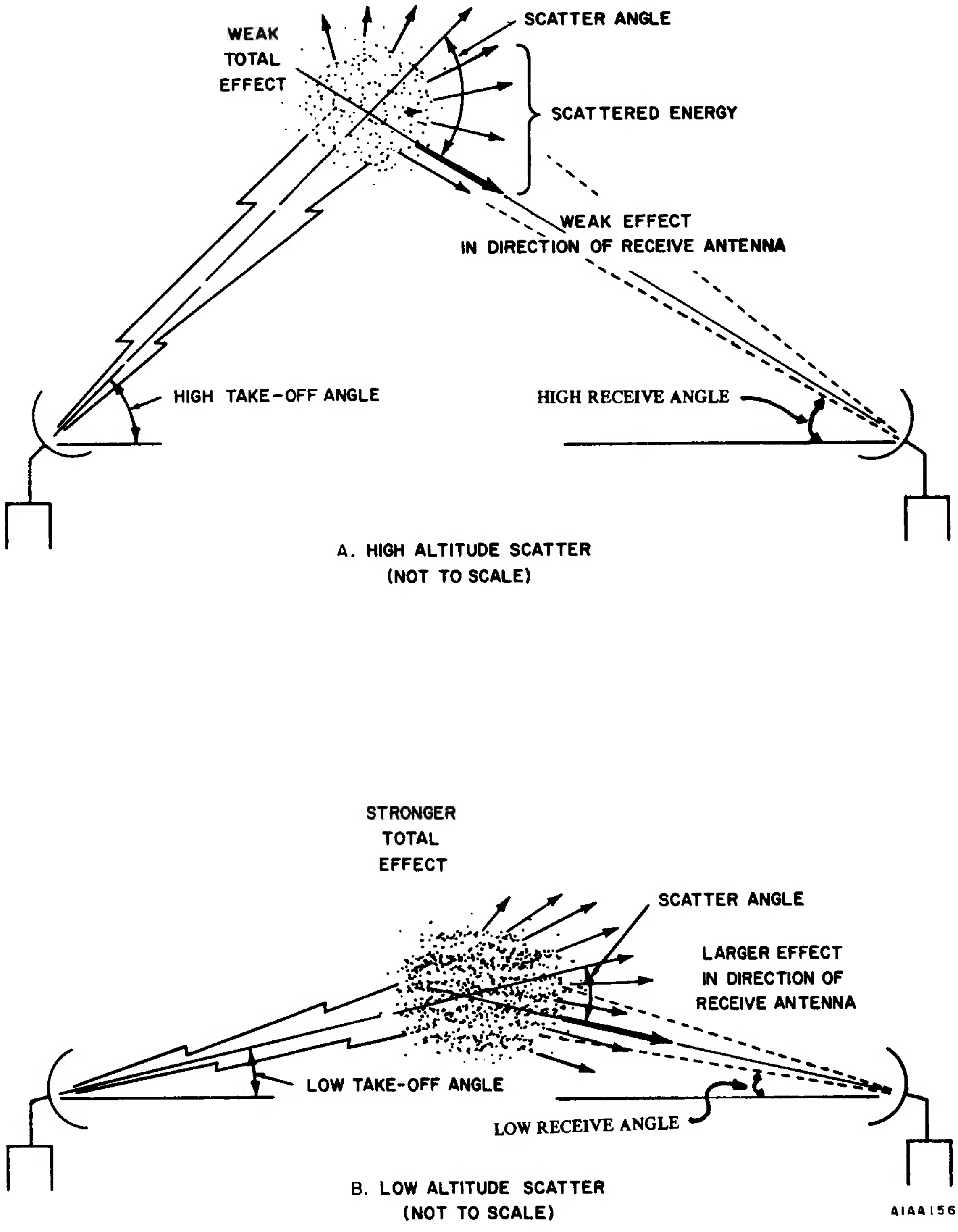


Figure 4-1. Effect of Take-Off Angle

If one or both antennas utilize a large take-off angle, the common scatter volume would be larger due to the increased distance, but the amount of energy deflected toward the receiving antenna would be reduced due to the much larger scatter angle. As stated previously, the higher altitudes exhibit much less scattering, consequently the effective received power decreases rapidly with increased altitude and scatter angle.

As stated in chapter 2, radio energy at microwave frequencies follows a slightly curved path. In a uniform atmosphere where the change radio refractive index is gradual. The bending or refraction of the radio wave may be essentially continuous, so that the beam is gently curved toward the earth.

Under that condition, the radius of the earth appears to the microwave beam larger than the true radius, that is, the earth appears flatter because of the tendency of the beam to refract downward in the atmosphere. The ratio of this apparent or fictitious earth's radius to the actual of the earth is referred to as the "K factor". The surface radio refractivity (N_S) during "Standard" atmospheric conditions is 301, the K factor is 1.333 (4/3). The effects of the variation in K is shown in figure 4-2. In practice, the value of K = 4/3 is only a mean value occurring in temperate climates. The usual variation in K is between 1 and 2, with the lower values existing in cold or dry climates and at high altitudes. The higher values of K are common in coastal areas where the humidity is high. Superstandard values of K from 2 to infinity, and substandard values from 1 down to 1/2 are encountered occasionally in the United States, mainly in tropical coastal areas.

An analysis of a troposphere scatter path requires the construction of a path profile containing all the obstructions in the line of propagation. To aid in the analysis, the effective earth's curvature should be used in order that the microwave paths can appear as a straight line.

To calculate the scatter loss, the scatter angle must first be determined. The derivation of the scatter angle θ_{oo} for the smooth earth case is shown in figure 4-3. The two obstacle path geometry shown in figure 4-4 is most common and is derived in a similar manner. Before starting calculations, a path profile should be constructed to determine the required antenna heights and the top of the highest obstructions in route.

4.1.2 Transmission Loss

The transmission loss is defined as the sum of the terminal losses and propagation losses. The propagation loss is the total loss in signal between an isotropic antenna located at the transmitting antenna site and a similar antenna located at the receiving site. At a later stage in the system calculations the terminal losses, antenna directivity gain, and antenna coupling losses are considered.

The long term median basic transmission loss in a forward tropospheric scatter path is:

$$L_{bsr} = 30 \log f - 20 \log d + F(\theta d) - Fo + Ho + Aa \text{ dB} \qquad (4\text{-}1)$$

where:

f is the transmitted frequency in megahertz
d is the mean sea level great circle distance in kilometers

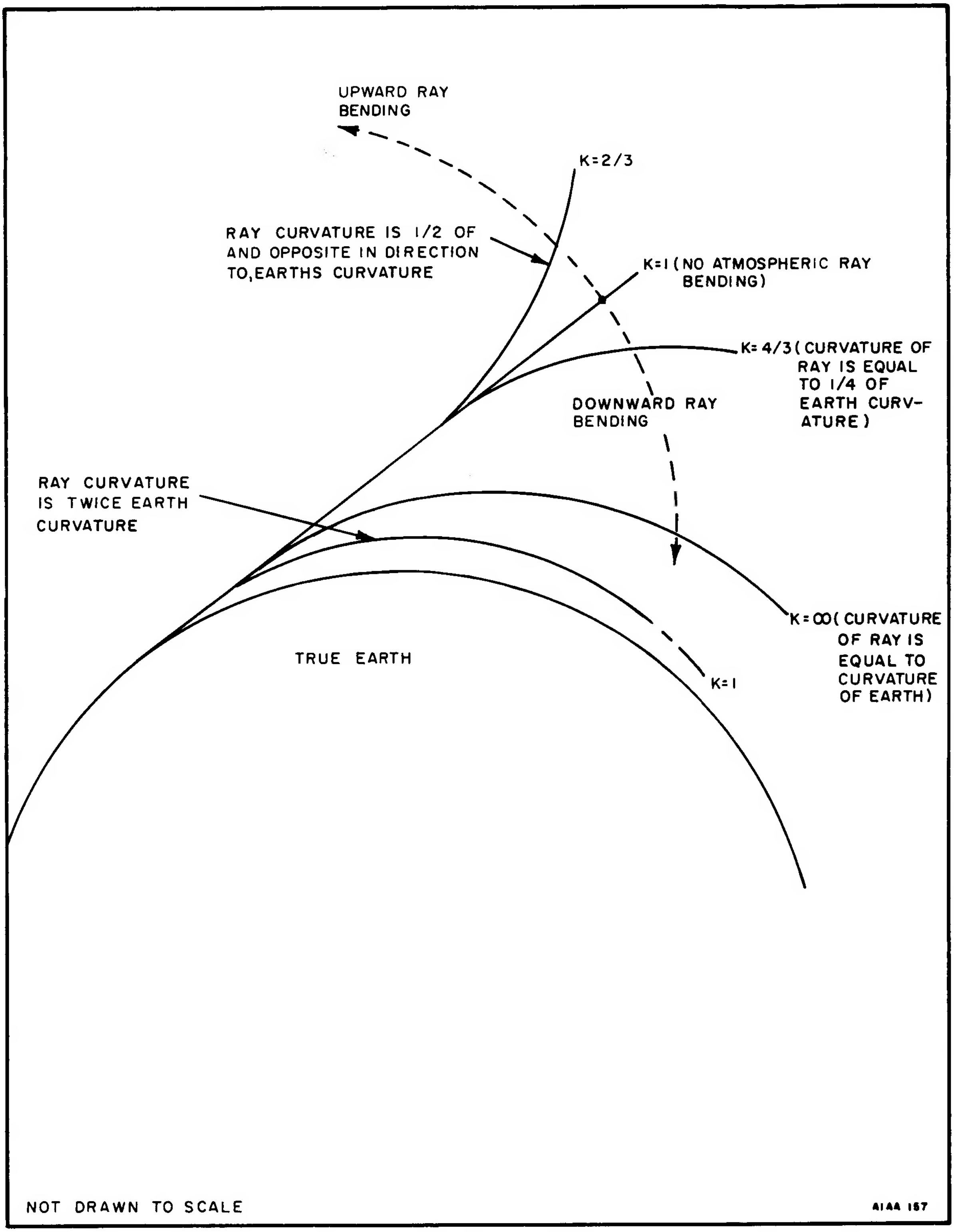
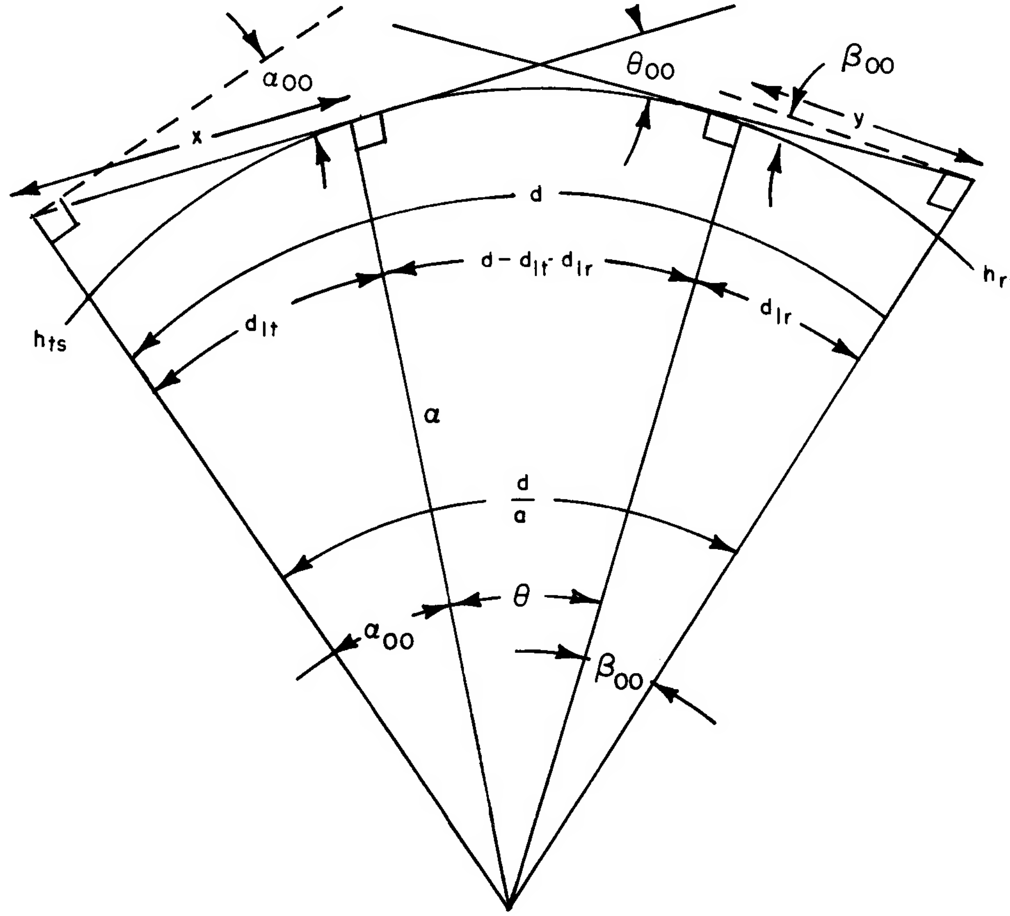


Figure 4-2. Kin Terms of Ray Bending



$\theta_{00} = \dfrac{d-d_{lt}-d_{lr}}{a} = \dfrac{d}{a} + \alpha_{00} + \beta_{00}$ RADIANS (α_{00}, β_{00} ARE NEGATIVE QUALITIES)

$x^2 + a^2 = (a + h_{ts})^2$

$x \approx d_{lt}$

$(d_{lt})^2 + a^2 = a^2 + 2a\,h_{ts} + h_{ts}^{\,2}$

$d_{lt}^{\,2} = 2a\,h_{ts} + h_{ts}^{\,2} \approx 2a\,h_{ts}$

$d_{lt} = \sqrt{2a\,h_{ts}}$

SIMILARY, $d_{lr} = \sqrt{2a\,h_{rs}}$

$\theta_{00} = \dfrac{d}{a} \dfrac{\sqrt{2a\,h_{ts}}}{a} \dfrac{\sqrt{2a\,h_{rs}}}{a}$ RADIANS

WHERE: d, a, h_{ts}, AND h_{rs} ARE IN SAME UNITS

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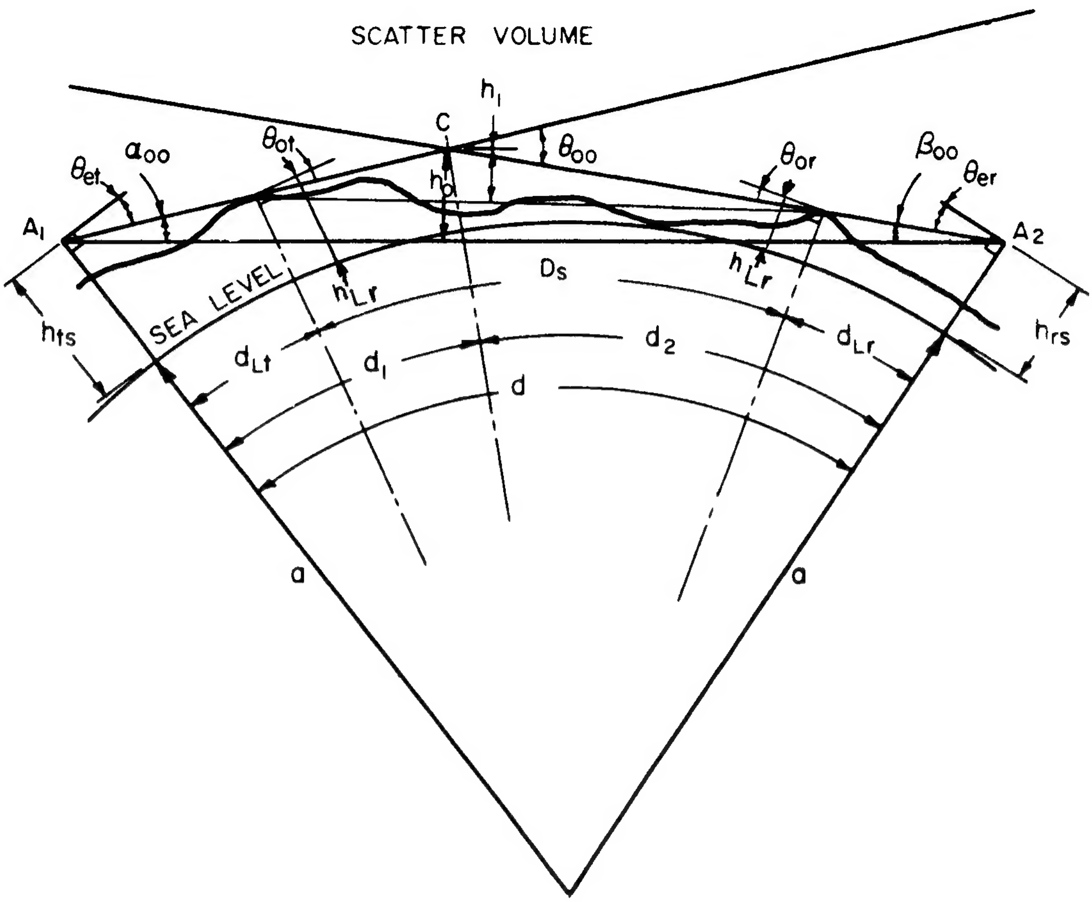
Figure 4-3. Derivation of θ_{00} for Smooth Earth Case



DISTANCES ARE MEASURED ALONG A GREAT CIRCLE ARC.
DISTANCES AND HEIGHTS ARE MEASURED IN THE SAME UNITS.

$$\theta_{oo} = \frac{D_s}{a} + \theta_{ot} + \theta_{or} = \frac{d}{a} + \theta_{et} + \theta_{er}$$

$$\theta_{et} = \frac{h_{Lt} - h_{ts}}{d_{Lt}} - \frac{d_{Lt}}{2a} \text{ (rad)} \qquad \theta_{ot} = \theta_{et} + \frac{d_{Lt}}{a} \text{ (rad)}$$

$$\theta_{er} = \frac{h_{Lr} - h_{rs}}{d_{Lr}} - \frac{d_{Lr}}{2a} \text{ (rad)} \qquad \theta_{or} = \theta_{er} + \frac{d_{Lr}}{a} \text{ (rad)}$$

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Figure 4-4. Two Obstacle Path Geometry

$F(\theta d)$ the scattering efficiency and Ho the frequency gain function are discussed in later sections.

As stated previously, the exact mechanism of tropospheric scatter propagation is complex and unknown. In addition to calculation of the propagation loss, while being the most critical computation in the system performance, is also the most ambiguous. There is no exact method to determine the scatter loss; rather, it can only be estimated from empirical data. In addition, the loss varies both on a fast, short term basis and on a long term slowly varying basis. A discussion of these will be made later in the text. For the present, it will suffice to say that the scatter loss for a given path is not constant. It is a time varying quantity with both long and short term statistical distributions. Therefore the propagation loss must be indicated as either a median value or as a value exceeded for some other percentage of time.

L_{bsr} in equation 4-1 is the median basic transmission loss in dB on a forward tropospheric scatter path, for winter afternoons. That is, if hourly median values of the total propagation loss (excluding terminal loss) are measured during the months of November through April, between the hours of 1 PM and 6 PM, then L_{bsr} would be the median of these values. This loss is approximately 3 dB higher than the yearly median value.

The attenuation function $F(\theta d)$ depends upon the propagation path and the surface refractivity N_s. The function includes a small empirical adjustment to data available in the frequency range from 100 to 1000 Megahertz. Figure 4-5 may be used to determine $F(\theta d)$ for all scatter links where $\theta d \leq 10$. For values of $\theta d \leq 10$ the curve is valid only for paths with symmetry factors (s) from 0.7 to unity the symmetry factor.

$$s = \alpha o / \beta_{oo}$$

The last three terms in equation 4-1 may be neglected in most applications. The scattering efficiency term Fo corrects for the reduction in scattering efficiency at great heights in the troposphere. The Frequency Gain Functions Ho, is a correction term for ground reflection effects. If the antennas involved are sufficiently high, the reflections of radio energy by the ground increases the power incident on the scatters visible to both antennas and can increase the scattered power. As the frequency is reduced, the ground-reflected energy tends to cancel direct-ray energy at the lower part of the common volume of the antenna beam intersection and decreases the efficiency of the communications path.

At frequencies above 1 GHz attenuation of radio waves due to absorption or scattering by constituents of the atmosphere, and by particles in the atmosphere may seriously affect microwave links. At lower frequencies the total radio wave absorption by oxygen and water vapor for propagation paths of 1000 kilometers or less will not excees 2 decibels but may be appreciable at higher frequencies. Figure 4-6 is a plot of median oxygen and water vapor absorption losses based upon data taken in the Washington D. C. area.

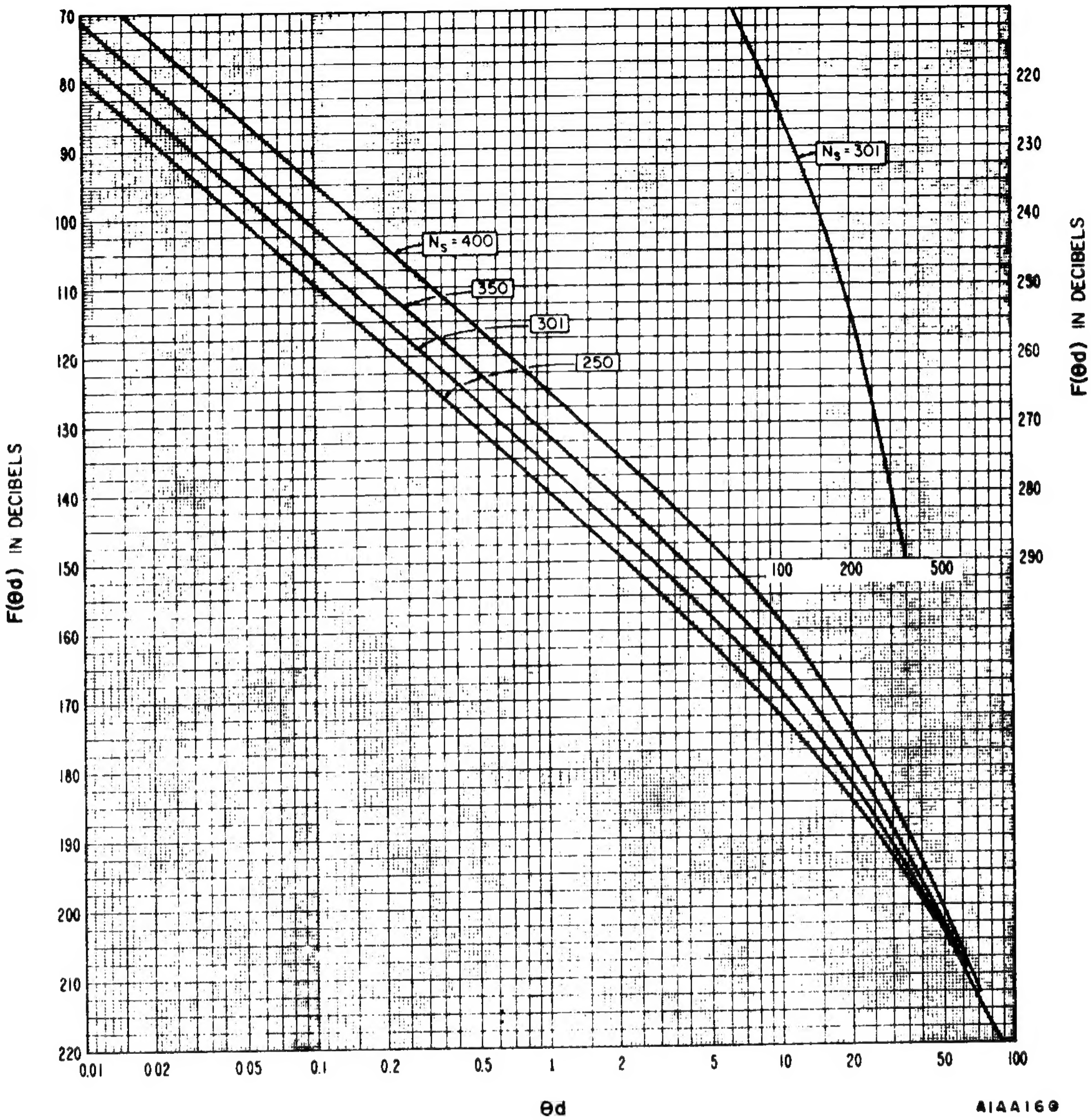

Figure 4-5. The Attenuation Function, F (θd) d is in Kilometers and θ is in Radians

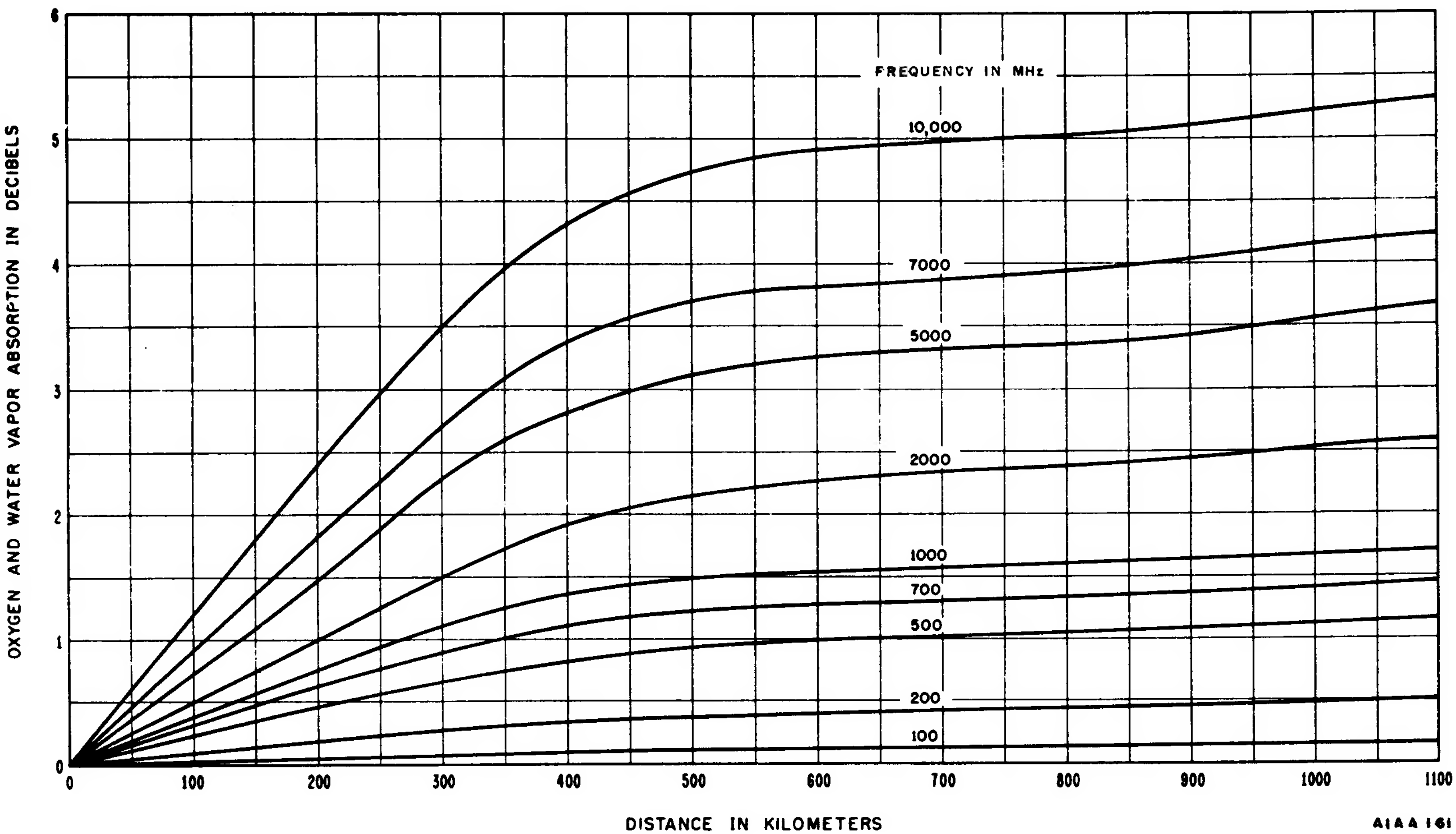

Figure 4-6. Median Oxygen and Water Vapor Absorption (August Data at Washington, D.C.)

4.1.3 Path Antenna Gain

The full plane-wave gain of an antenna, calculated on the basis of its diameter, in terms of wavelength and efficiency cannot be realized when used in the tropospheric scatter mode. The difference between the plane-wave gain and the realized gain is referred to as the aperture-to-median coupling loss. The aperture-to-median coupling loss arises from the fact that the scattered signal arriving at the receiver does not come from a point source, but from an extended volume subtending a measurable solid angle at the receiver. Thus, if the transmitting antenna is of very narrow beamwidth it will illuminate a volume of air space smaller than the effective size of the scatter volume when a broad beam antenna is used. Since the scatter volume is decreased, the signal arriving at the receiver will not increase in the same proportion as it would under free space propagation conditions. This difference between the free space expected-gain of a narrow beam antenna and its measured gain on a scatter circuit is termed "antenna gain degradation" or "antenna-to-medium coupling loss" and has been theoretically determined to be proportional to the ratio of the scatter angle (0) to the antenna beamwidth (Ω).

4.1.4 Fading

A scatter signal at a particular instant is the resultant of a number of individual signals arriving with random phase differences. For short periods of time the random variations of these phase differences produce a signal of varying amplitude, which tends to be Rayleigh distributed. Over long periods of time, the scatter signal assumes a log-normal distribution.

In the early stages of troposcatter communications it was soon recognized that the short term distribution always approximated to a Rayleigh curve. The short-term Ravleigh distributed signal variations are independent of the season but are brought about because of the nature of scatter propagation. The received signal is composed of components of random phase from different points in the scatter volume. The sum of these components is constantly varying. The effects of the short term fades were found to be minimized by diversity.

The short term fading of the scatter signal, during the hour, is assumed to follow a Rayleigh distribution. The cumulative Rayleigh distribution curve is shown in figure 4-7. This curve, identified as "Rayleigh Fading" in the figure, shows the percentage of the hour that a given received power level, in dB, is exceeded (upper abcissa scale). Power levels are given in dB with reference to the hourly median value.

A technique that is widely used in troposcatter systems to eliminate, to a large extent, the effects of this fast fading is known as diversity. Diversity consists of transmitting the same information over two or more communications paths that have uncorrelated fast fading. The fact that the fadings on the paths are uncorrelated allows the separate signals to be combined into a single signal which is much more stable with respect to time.

Where two separate paths are provided, the scheme is known as two-fold (or dual) diversity; four paths, four-fold (or quadruple) diversity, etc. The resultant curves for two fold diversity are shown in figure 4-7 along with the no-diversity Rayleigh distribution. The terms Maximal-Ratio, Equal Gain, and Selection Diversity refer to the

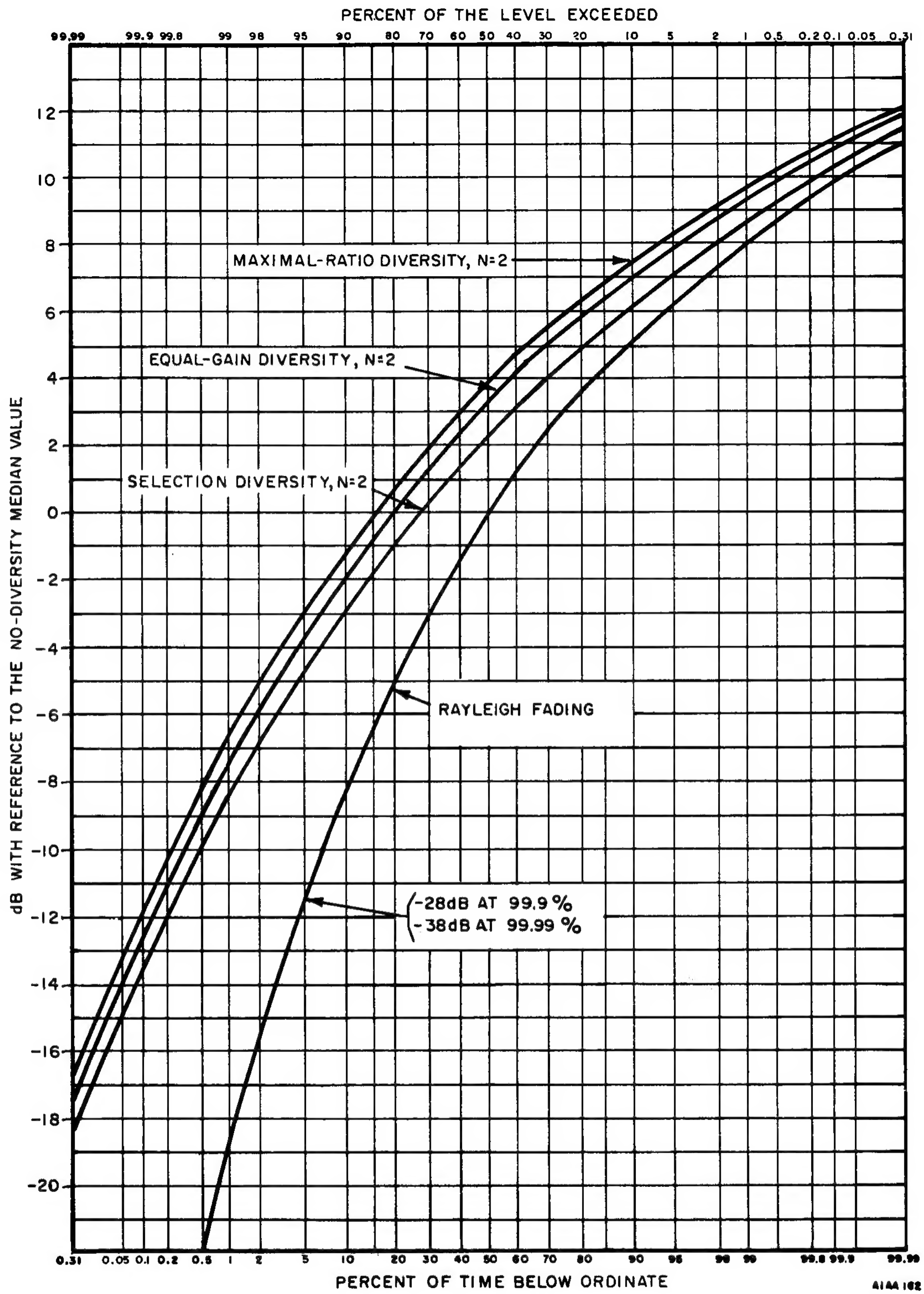

Figure 4-7. Short-Term Fading
(Two-Fold Diversity)

manner of signal combining employed. Briefly, a selector is a switching circuit that is continually choosing the signal with the higher power level; equal gain combining consists of the addition of the different signals to arrive at a single sum output; and, maximal ratio combining connotes the addition of the separate signals with the gain of each signal channel in the summing network proportional to the RMS signal level and inversely proportional to the mean square noise level, the same proportionality constant being used for each signal.

In figure 4-7 note that regardless of the type of combining used, a considerable provement is obtained by the use of diversity. Referring to the maximal ratio curve, it is seen that an hourly median (5 percent improvement, or gain, of 4dB is realized. (Note the median, or 50 percent point for the no-diversity Rayleigh curve is used as the 0 dB reference level). More important, we are concerned with the extreme fades occurring during the smaller percentages of the hour. For example, the level exceeded 99 percent of the hour stated in another way: the level which we are below for 1 percent of the hour is seen to be 18.5 dB below the reference median value where no diversity is used; whereas, for maximal ratio combining two-fold diversity, the 99 percent level is only 6.5 dB below the median reference level. Thus, a 12 dB gain is obtained when the 99 percent point is considered.

Clearly, the extent of improvement, or gain, that a diversity system provides is function of the percentage of the hour with which we are concerned; thus, so-called median gain values are sometimes misleading. The true value of diversity lies not in the median gain, but in the fact that it "flattens out" the no-diversity Rayleigh distribution. With diversity, short term signal fluctuations are almost negated, leaving only the long term signal variations to be contended with.

The fading distributions for four-fold diversity are given in figure 4-8. While the improvement obtained from two-fold diversity over no-diversity is considerable, the further improvement received by using four-fold diversity is also quite significant. The signal level exceeded for 99 percent of the hour with four-fold maximal-ratio diversity is almost 1 dB better than the signal exceeded 50 percent of the hour (i.e., median value) with no diversity.

In conventional tropospheric scatter systems four-fold diversity is usually used. Aside from the better performance provided, a redundant two fold diversity scheme is also maintained in this manner. This significantly reduces circuit outage time resulting from equipment failure. In post-detection combining schemes the maximal ratio technique is usually used, while in pre-detection combining, an equal gain combiner is normally utilized. Pre-detection equal gain combining gives almost the same gain as post-detection maximal ratio combining and at the same time decreases below-threshold outage time and reduces the size of the necessary equipment.

Aside from the short-term Rayleigh distributed fades, long term fading is encountered on tropospheric scatter paths. This is a variation in the hourly median received power level due to changes in refractive index, changes in the nature of the scatter volume, etc. Long term fading here will be used to connote variations from hour to hour while short term fading is used to identify signal fluctuations within the hour. To date, the use of diversity has not been found to have any appreciable effect on these long term

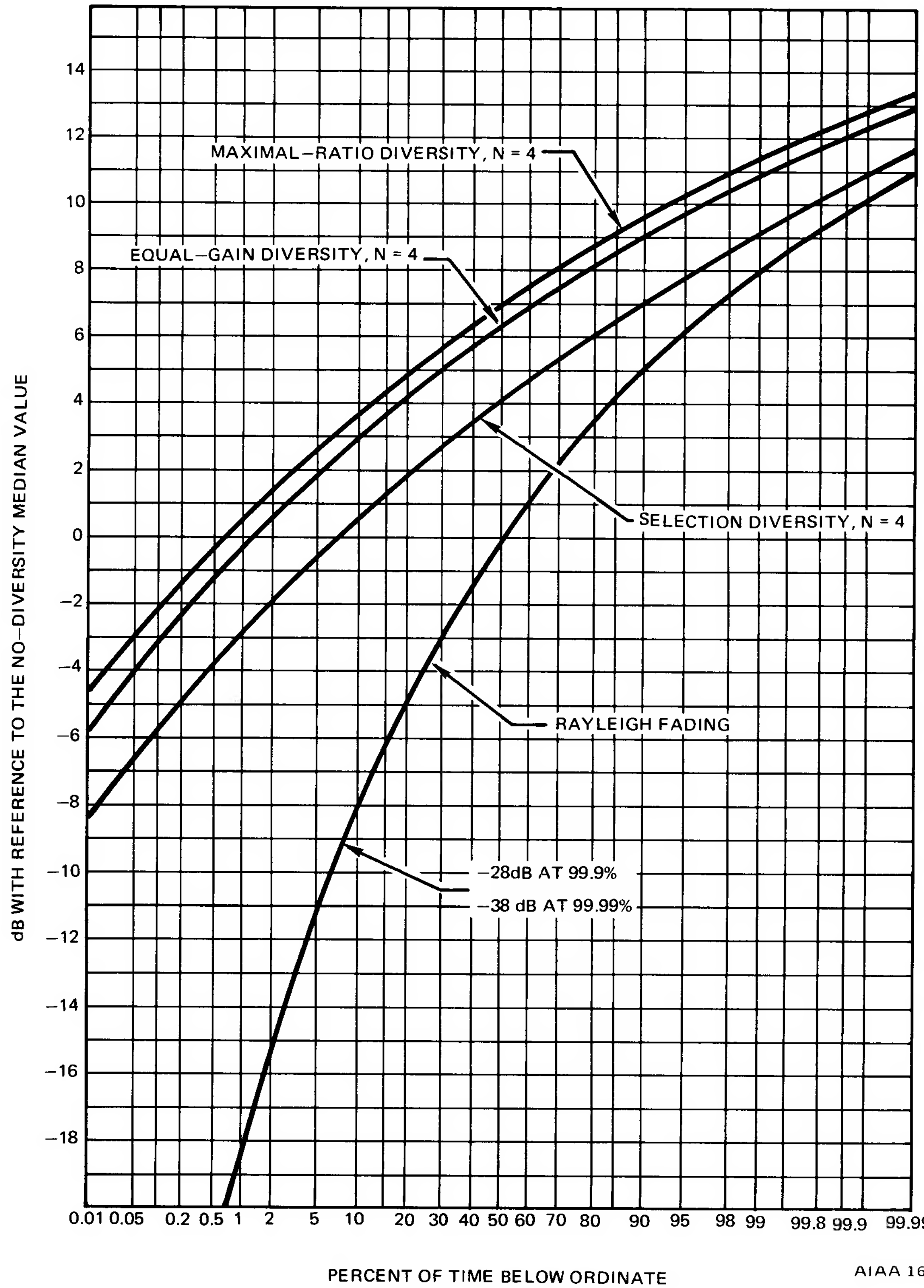

Figure 4-8. Short-Term Fading
(Four-Fold Diversity)

fades. The design procedure is generally to determine the maximum severity of fading to be encountered and then design the equipment complement to meet minimum performance requirements during the worst part of the year.

Long term median signal variations are due primarily to weather and seasonal changes. The slow signal fluctuations come about mainly because of the changes in atmospheric refraction.

The median path loss is usually greatest during the winter, being at times, of the order of 20 dB in excess of that observed for the equivalent period of measurement carried out during the summer. Upward bending of the radio beams in the colder portions of the year tend to increase the scattering angle of the path and thus increase the scattering loss. In addition extreme climatic variations could cause ducting or introduce new path obstacles which in turn could cause abrupt variations in the received signal.

4.2 NOISE

The total noise in any tropospheric scatter system is composed of the noise contributions of several types including thermal, intermodulation, interference and multiplex noise. Distortion appears intermodulation noise. With the exception of path delay distortion, all noise and intermodulation effects are treated in chapter 3.

The beam of microwave energy is not a single line but a wavefront extending for a considerable distance about the centerline. At 120 kilometers an antenna beam of 0.5 degrees would be approximately 1 kilometer wide. The received wave is the sum of a large number of reflections within the common scatter volume of the transmit and receive antennas. The path delay distortion is caused by the differences in path lengths from transmitter to receiver via the various scatter points within the common scatter volume. Using the path length along the centerlines of the two antenna beams as the median path. The maximum path delay error is based upon the energy along the most elevated edge of the antenna beams. This delay in seconds is defined as

$$\Delta = \left(\frac{d}{c}\right)\left(\frac{\Omega}{2}\right)\left(\frac{\theta}{2} + \frac{\Omega}{2}\right) \quad \text{seconds}$$

where

d is difference in path lengths
c is the velocity of light in Km/sec
Ω is the beamwidth of the antennas in radians
θ is the path angular distance in radians.